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FLOOD-EROSION PROTECTION FOR HIGHWAY FILLS

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HIGHWAY DIVISION

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FLOOD-EROSION PROTECTION FOR HIGHWAY FILLS

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SYNOPSIS

In this investigation, which was sponsored by the Highway Research Board of the Iowa State Highway Commission, a method has been developed for constructing highway fills so that they will not be appreciably damaged by inundation, even when accompanied by high velocities of flow over the grade or along the side slopes. Preliminary investigations shed new light on the mechanism of failure of erosion protection, providing a rational basis for a design capable of being built up to any required degree of resistance to scour. The design recommended embodies properly graded layers, with the topmost bound in rock sausages. The size of sausages required for various exposures was not determined but full-scale tests showed that a minimum practicable size would be ample to protect highway fills under the most severe conditions likely to be encountered in Iowa.

The Problem

Before the advent of the high-speed motor vehicle and of earth-moving machinery of great capacity, the highway was usually built across the flood plain almost at grade, rising to cross the bridge which was set just above the estimated high-water elevation. When floods came, the approaches were soon inundated, and the bridge, which was probably still dry, rendered useless.

The demand for a highway that would be open at all times, which developed as the economy became more and more dependent upon motor transport, has resulted in a different type of valley crossing. High fills extend out from the hills on each side to meet the bridge without any intervening sag in grade, even where the flood plain is comparatively broad. Sight distances are better, with fewer and broader vertical curves, and the hills at the sides of the valley are less high and less steep. With these incidental benefits, the new design seems to be a great improvement.

When subjected to floods somewhat above ordinary high water, however, serious defects are exposed. The waters that formerly flowed over the approaches now have to crowd through the bridge openings. The bridge opening is not adequate, and the water is backed up, giving higher elevations upstream than would previously have existed at the same discharge, and resulting in greatly increased velocities through the bridge with attendant danger from underscour. Velocities approaching the bridge opening along the side of the fill often became high enough to wash out the shoulders and undermine the pavement slab. If the flow is constricted enough so that flood waters overtop the pavement, heavy damages can occur when the depth of overflow is less

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than a foot within comparatively short periods of time. As an example, on June 26, 1944, Sugar Creek, a tributary of the Cedar River, near Moscow, Iowa, had a flash flood which washed out several modern-type bridge crossings and a considerable length of pavement, but did little damage to the old-type crossings which were passable as soon as the flood waters had subsided.

It is hardly necessary to add that wash-outs in high approach fills are extremely dangerous to traffic and expensive to repair.

Some Possible Ways of Improving the Modern Type of Valley Crossing

In most locations the bridge openings could be increased as to accommodate the largest floods considered to be possible without any delay to traffic. For an important highway a comparatively large expenditure on the crossing will be justified, and the flood chosen for the bridge-opening design might be one which could be expected to occur only once in every twenty-five years, or every hundred years, or even a longer period of time. On the other hand, bridges for a less important highway might be so constructed that it would be rendered impassable, on the average, once in every five years, or even a shorter period of time. A reasonable economic balance could be struck between the losses to traffic and the cost of eliminating flooding, providing that washouts, with their uncertain cost, can be eliminated.

One solution to the problem which, though not entirely satisfactory, has proven to be the best answer under some circumstances, is to lower the grade line or use less erosion-resistant construction at certain carefully chosen sections, with the expectation that a rare great flood will wash them out. These "fuse-plug" sections, which must be of ample hydraulic capacity, are located at points where the high-velocity jet that will flow through them will not endanger the bridge, either directly or through induced eddies, and where damage to adjacent properties will be the least. At the same time, consideration should be given to the speed and ease with which the washed-out fill and surfacing can be repaired. The disadvantages of this method, as well as its economies, are evident.

Another method which has been frequently tried is to surface the fill with a masonry slab. Obviously very expensive, such protection is doomed to failure. This is well known to the builders of earth dams, whom sad experience has taught never to attempt to build a spillway by placing masonry paving over filled ground. The reason is that full hydrostatic pressure may gain access to the lower side of a slab which has little or no pressure above it. Unless the slab is heavy enough to balance the excess pressure, a blow-up will result. For example, a concrete thickness of 20 inches would be required to balance only four feet of water.

Mechanism of Rip-Rap Protection

Since prehistoric time earth threatened with erosion has been protected by piling on stones or other loose objects. The stones may be simply thrown together or they may be carefully placed for neat appearance. The cost varies greatly, depending upon the availability of stone and the labor expended in placing. The effectiveness varies greatly, also, but does not necessarily bear any relation to the cost or to the appearance. The layer of stones is supposed to protect from erosion by reducing the velocities that come into contact with the earth to a non-eroding value. The stones exposed to the current must be of such size and weight as to resist removal.

In order to study how a layer of stones reduces the velocities at the surface of the material being protected, a glass-walled flume 27 inches wide was constructed in which the erosion from water flowing over layers of crushed stone or gravel of different thickness protecting a bed of fine sand could be observed throughout a length of 48 inches.

Before the rock layers were placed, the sand bed, of fine white sand, was leveled and carefully covered with a thin layer of red sand of the same size classification. This layer was as thin as it could be and still cover the white sand. The rock particles were then carefully placed by hand in such a way as not to disturb the red sand, but not in any systematic fashion to secure good fit or minimize voids. After a safe thickness of rock particles had been placed by hand, the remainder was dumped in to the required level.

Up- and downstream from the 48-inch section, the flume had a bottom which formed a straight line, on slight down-grade, with the top of the protective layer of crushed stone or gravel. As the discharge was increased, the velocity and erosive power of the current over the test section was thereby increased.

The method of operation was to increase the discharge slowly, step by step, and to note the point at which the sand grains in the thin red layer began to be displaced. The apparatus also permitted observation of the way in which erosive velocities reached the bed. Grains of potassium permanganate distributed through the rock layer gave off streamers of colored water which could be traced for several inches, and which indicated to some extent the intensity of the local velocity. Before the tests started, it was thought that the principal medium by means of which the erosive velocities would reach bottom would be by induced eddies; rotation in the top-most cavity would induce opposite rotation in the next, and so on down with decreasing intensity. Observations showed very little of this action. It was noticed that the streamers over wide regions tended to be roughly parallel, and to fluctuate together in direction and intensity, indicating that the main currents in the underflow were driven by the pressure differences originating from the main flow of the stream.

As the discharge increased, the intensity of these currents through the rock layer increased until finally the most violent bursts would begin to move the red sand at several points which could be observed through the glass wall. If the test was stopped at this point and the stones carefully removed by hand, the points of beginning movement were found to be uniformly scattered, in random fashion, over the whole area of the sand bed. If the test was not stopped, but the discharge increased further, movement began at more and more points and rock and sand began to be mixed instead of having a sharp plane of demarcation.

Uniform Rip-Rap

The first investigation with this apparatus was conducted with stone of uniform grading.(1) The results, Fig. 1, show that it would be uneconomical to use material of uniform granular size to protect finer material, since a great increase in thickness of protective layer is required for only a slight increase in velocity. This result is consistent with the observation that the pulses driven by turbulence in the stream were more apt to cause erosion than the void eddies.

Specifications for Graded Rip-Rap

It was decided next to try non-uniform grading of the protective layer, particularly a certain type of grading proposed by Karl Terzaghi and thoroughly tested by the U. S. Waterways Experiment Station at Vicksburg, Mississippi. This grading is intended to be proof against the escape of the bed material into an overlying coarser layer when the flow is directly upward. In the Vicksburg tests the layers subjected to upward flow could at the same time be vibrated and subjected to surging without causing the fine material to migrate upward into the coarse, but to achieve this the original specifications suggested by Terzaghi had to be slightly revised.[2],[3] The resulting specifications relate the grading of the protective layer to that of the bed material by the following inequalities:

$$\frac{D_{15}\text{ Filter}}{D_{85}\text{ Base}} < 5$$

$$4 < \frac{D_{15}\text{ Filter}}{D_{15}\text{ Base}} < 20$$

$$\frac{D_{50}\text{ Filter}}{D_{50}\text{ Base}} < 25$$

Fifteen per cent, by weight, of the filter material (the protective cover) is finer than the size indicated by "D_{15} Filter;" 85 per cent, by weight, of the base material (the material being protected) is finer than the size denoted by "D_{85} Base;" etc.

Figure 2 shows grain-size curves for materials meeting the Terzaghi-Vicksburg specifications, which will hereinafter be referred to as "T-V gradings." The "base" layer (loess) is to be protected by the "filter" layer (sand). From the grain sizes of the 15, 50, and 85 percentiles of the loess, the limits on the grading of coarser material that will protect it are determined by the Terzaghi-Vicksburg specifications. Sand "A" is about as coarse a sand as could be used for the loess shown. Sand "B" would be all right, but being finer than necessary, would set lower limits on the crushed rock layer next above, which has to have the same relationship to the sand that the sand has to the loess.

Notice that since the abscissa scale is logarithmic, each of the 4x, 5x, 20x, and 25x multipliers in the inequalities corresponds to a fixed horizontal distance on the graph; hence readings and computations are not necessary in plotting the permissible limits. When two materials have to be blended to meet the specifications, computations are still not necessary since the grading curve of a blend divides the vertical distances between the curves of its components inversely according to their proportions. Thus the curve for a blend composed of two-thirds sand "A" and one-third sand "B" of Fig. 2 would contain 80% finer than the 1.0 mm size.

Protective Quality of Graded Rip-Rap

Tests of the T-V grading in the same apparatus as was used for the tests of the protective layer of uniform grain size showed a two-inch layer of T-V grading to give better protection over most of its area than an eight-inch layer of uniform particles of the same size as the largest component of the T-V mix.[4] Since the largest particles of the T-V mix barely passed a 3/4 inch mesh sieve, it is not surprising that the 2-inch layer showed a few imperfect

spots. A 3-inch layer of T-V grading gave complete protection over the whole range of velocities up to that which rock began to be torn from the top of the protective layer, making it necessary to stop the test. In additional tests, in order to compensate for the uniformity of the flume as compared with a natural stream, the bed and protective layer were subjected to upward flow simultaneously with overflow. No motion was observed even when upward-flow velocities approached those which would raise the whole mass by friction drag.

A surprising result of the tests with the uniform-sized material and the T-V grading was that the latter not only protected the bed better, but was less subject to removal itself by the flowing current. It was expected that the finer particles would be removed from the mix by the current, but such was not the case.

Since the two gradings, uniform and T-V, had great differences in their protective and erosion-resistive qualities, it might seem worth while to make similar tests of other gradings. From the observations of the mechanism of protection and consideration of the theoretical basis of the T-V grading it would seem that no grading could be found that would be much better than the T-V grading in its protective qualities. Whether this conclusion would hold with respect to erosion-resistive properties is perhaps open to some question.

Another question is that of particle shape. Both angular (crushed limestone) and rounded (river gravel) particles were used without finding significant differences, but the results from particles of very unusual shape (elongated or flat) might be significantly different.

Corroboration of the conclusion that erosion of fine material from under the protective stones must be prevented is given by Karl Jetter, who made an extensive investigation of methods of protecting sand dikes which had been proposed to maintain navigation depths on the upper Mississippi.[5] He thought that the downward currents between the stones might be prevented from scouring the sand by means of a watertight covering, apparently forgetting the concomitant upward currents and pressures which would surely disrupt such a covering. He rejected the idea of a concrete mat, however, for it "would be expensive and any rupture in its surface would permit scouring of sand." Also, he thought that for the upstream slope and berm satisfactory results "might be obtained by grading the covering from coarse sand next to the sand of the dike to large stones, heavy enough to withstand the current, at the top."

Erosion Resistance of Graded Rip-Rap

It was assumed at this stage of the investigation that the problem of protecting the earth fill at its zone of contact with the protective layer was solved, and that what remained was to learn how to prevent the protective layer itself from being washed away. Just as the T-V layer protects the earth, another layer of coarser material bearing a T-V relationship to the first one can protect it, and so on, until finally a layer is reached with particles large enough to resist movement by the stream velocities likely to be encountered. The problem is to find just how large the grading of this protective layer needs to be.

Erosion conditions are severe on a steep slope with water flowing directly down the slope since gravity and the dynamic force from the water both have components down the slope, while the only resisting forces are compression

in the top layer and friction along its bottom. Previous analyses and attempts to develop a formula that would give the necessary size of rock, as recorded in the literature, were not made for T-V gradings, and lacked verification on slopes as steep as would be necessary for highway fills. Hence, another flume was built at the Iowa Institute of Hydraulic Research in which a T-V layer representing the top layer on the downstream face of a full-scale highway fill could be tested with varying depths of overflow over various sizes of aggregate placed to different side slopes. Limitations of space and water supply available at the time fixed the width of the flume at only fifteen inches. It was decided that the largest aggregate particles should not have a maximum dimension of more than six inches in order to avoid wedging between the sides.

Despite the greatest care in the use of this flume, it was difficult to obtain consistent quantitative results. At the same time that it was being operated, a full-scale highway fill section was built in the river flume of the Iowa Institute of Hydraulic Research. The ten-foot width permitted the use of larger rock, and that which was used was the largest that could be obtained from the local quarry. The fill section was not a full standard highway section since it lacked a slab, and the upstream section was replaced by a bulkhead and flow guide. Also, the shoulders were narrower than usual. These changes from standard were made to cut expense, and were not considered disadvantageous as far as possible results were concerned since their effect would be to increase slightly the severity of the exposure. The loess fill was protected by T-V layers which might be loosely described in ordinary terms, as sand, fine gravel, coarse gravel, and rip-rap to 14-inch maximum size. A total weight of 250 pounds of hot asphalt was poured on top of the rock in a grid pattern of lines at one-foot centers to increase its erosion resistance. By extrapolation from the results of the tests in the smaller flume, it was thought that this fill should stand an overflow head of about one foot. Actually, some movement of the rip-rap occurred within five minutes after the head had reached one foot, and the eroded patch enlarged rapidly during the next run of ten minutes at a head of 0.7 foot.

Before the results of this test in the river flume were available, another series of tests with the larger rock sizes was started in the 80-inch flume of the Rocky Mountain Hydraulic Laboratory at Allenspark, Colorado. Finally, all three series of tests were completed. The results are shown in Fig. 3. All of the tests shown were made with the tailwater at the lowest possible elevation, a series of preliminary tests in the 15-inch flume having shown that the condition of low tailwater was most likely to cause failure of the rock slope. It had been thought that the hydraulic jump that would form with moderate tailwater depths would aggravate the tendency to scour on the steep slope, but this was found not to be the case.

Although the rip-rap tests in the three flumes were inconclusive in determining the size of the rock in the topmost layer needed to resist various depths of overflow when covering reasonable highway-fill side slopes, one important result was perfectly evident; the rock sizes required for even moderate depths of overflow would be so large as to be impractical for the purpose and would be prohibitively expensive in many localities. Despite the care used in the laboratory tests, there was great variation in the results. Under field conditions the variation would undoubtedly be even greater.

Rock Sausages

It was next decided to try a scheme modeled after a device probably first used by the Chinese many centuries ago, and suggested by Dr. C. H. Yen's description of closure works on the Yellow River. The top T-V layer was stuffed into wire sausages and laid over the fill. By pulling the wire sausages up tight, the rock was put into compression, so that the layer gained compressive strength in the direction of the slope. The cross-sectional area of the wire in the sausage, if carried over the top of the fill, would also provide a force to help carry the large downward force on the steep slope. The idea was first tried in the Rocky Mountain Hydraulic Laboratory erosion flume using 2-ft chicken wire which when stuffed with rock of 3-inch maximum size made sausages about 9 inches in diameter. Laid on a 3-1 slope, starting at the upper edge of a narrow "shoulder," and hence without the benefit of tension to hold them in place, these sausages withstood a greater depth of overflow than any loose layer tested, and in fact constituted the only installation which remained in place up to the capacity of the flume.

The final test was of a loess fill built during the autumn of 1953 in the river flume of the Iowa Institute of Hydraulic Research, and protected by layers approximating the proper T-V gradings, consisting of sand and of fine crushed stone layers below the 12 to 15-inch diameter sausages which were made of No. 9 wire spiral woven to a two-inch mesh. The crushed stone available to fill the sausages was crusher-run stone passing a 6-inch screen and retained on a three-fourths inch screen. The grading was not quite right, according to T-V requirements, for the layer next underneath, and was somewhat too small for the wire mesh openings. The first row of sausages was filled in position and laced up tight, but since the smaller rock particles tended to spill out, the remainder of the crushed stone was sifted to eliminate the sizes passing the two-inch mesh. This operation had to be done by hand, since the necessary equipment was not available, and due to the magnitude of the job, it was not completely effective. The rest of the sausages were filled from the end, in ten-foot lengths, and laid in place with a crane. The longitudinal spaces between the sausages, underneath the line of contact, did not get well filled with rock and hence formed channels down the slope through which the underlying fine rock could be washed away, as shown by a preliminary test (Run No. 1) made on December 8, 1953, with the highest head available up to that time. After this test the sausages were wired together end to end and some small gaps on the downstream face were closed with chicken wire.

Despite the imperfections, the test section withstood depths of overflow up to 0.75 feet for over a half an hour in this preliminary test without appreciable signs of damage. Professor A. Alin, Emmet Laursen and the writer witnessed the test, which gave rise to such a degree of confidence that it was felt that a progress report should be made available to the profession.[6]

Previous uses of Wire-Bound Rock Sausages

During the preparation of the progress report it was learned that "rock sausages," or "gabions," as they were called, had been in use for fifty years or more in the Himalayas, and after the report was published, it was found that an Italian firm specialized in "gabions" for erosion protection. Its brochure states "if the gabion sinks, no matter, another one can be built on top," which would seem to indicate that the importance of T-V grading to

protect the bed material had not been discovered. With the method of hand-filling bags and rectangular box cages, it would also seem that the benefits from putting the loose rock in compression would not be obtained. The fact that the firm has been successful for so many years, in spite of these omissions, speaks well for this type of construction.

Another response brought forth by the progress report was from Mr. L. R. East, Chairman of the State Rivers and Water Supply Commission, of Victoria, Australia. He cited a published report by H. G. Strom that includes a description of the wire sausages used for river control practice in Australia.[7] In discussing the procurement of filling material for the sausages, Mr. Strom writes as follows: "If time and economy do not permit selecting the larger stones, mixed stone and gravel may be tipped in just as it comes from the river bed. The coarser stone will stay in the tube; the finer will fall through the mesh, but much of it will lodge between and below the tubes and act as a sort of inverted filter, to give additional protection to the bank against currents or wave action. If this 'run of the bank' filling is used, a smaller mesh will hold more of the gravel."

Under "Notes on the Use of Loose Stone" Mr. Strom writes "If the material of the bank is friable, stone in pieces big enough for stability may leave voids large enough for currents or wave-lap to leach or fret the bank-material away from behind the stone. This tendency may be checked by placing a layer of finer broken stone or gravel against the bank, and then placing the heavier stone over this." It is seen that at points his thinking, like that of Mr. Jetter, came very close to the results of the present investigation.

It should be noted that in the foregoing records of use of rock sausages, the purpose was river bank protection. There is no specific record of their use to protect relatively steep embankments from overflow, and it is probable that there was seldom an opportunity to install the sausages "in the dry," with opportunity to control the underlying layers as would be possible in the construction of most highway fills.

The late Mr. Andrew Wiess reported to the American Society of Civil Engineers on a similar method used to pass flood waters over the partially completed San Ildefonso Dam in Mexico.[8] Though imperfect from the standpoint of the requirements for an effective reverse filter, his design, which embodied a network of steel bars with anchors, was adequate for the purpose.

Completion of Test of Full-Size Overflow Section

In May and June of 1954, occasional higher flows in the Iowa River permitted testing the sausage-protected overflow section under more severe conditions, as follows:

Run No.	Date	Head in feet	Duration
1	Dec. 8	.75	20 mins
2	May 4	.9	20 mins
3	May 4	1.3 to 2.3	45 mins
4	May 4	2.2	2 hrs
5	June 3	2.5	3 1/4 hrs
6	June 7	2.7	1 hr
7	June 8-9	1.1	28 hrs

All of the runs were made with no tailwater, and velocities at the foot of the embankment, the total height of which was 5-1/2 feet, were estimated to be about twenty feet per second. No damage could be found after Run 2, but after No. 3 it was found that some rock had been removed from inside one of the sausages. No further damage was noted until after Run No. 5, when there was found to have been some enlargement of the cavities where undersized rock had been torn out through the mesh. After No. 6, the general level of the sausages seemed to have sunk slightly at one location, but the amount was no more than could have been accounted for by the fact that some fine rock had been washed out through the gaps between the sausages which had not all been effectively stopped up after the first run.

Finally, two of the sausages were slit longitudinally, and the embankment subjected to a head of 1.5 feet for 10 minutes. The sausages on the downstream slope were about half emptied, while those on the upstream slope were not affected. Further overflow failed to remove the installation sufficiently fast, and the sausages were finally lifted out with a crane.

It should be noted that the two tests in the 10-foot flume of the Iowa Institute of Hydraulic Research tested not only the resistance of the protective cover toward being removed, but also the ability of the T-V graded sequence to protect the underlying loess from being leached out. In neither case was there any sign that the loess was being removed while the layers above were intact. The first, of course, was not as severe a test of the protection, since with rip-rap bound together only by bitumen, the rock covering was rapidly washed out and the loess exposed. In the second test the flow was maintained at higher depth for many hours, but at no time was there any sign of the water being muddied by loess, nor any sign that the sausages had been undermined except at the location where a little of the rock layer next below the sausages seemed to have been removed.

Field Installation Needed

Under field conditions in Iowa, tailwater would stand on the downstream face, the total head would seldom if ever exceed three or four feet, and the flood flow would in most cases last for hours rather than for days. Hence it seems safe to recommend the installation of rock sausages for a full-scale field test at the first opportunity. Installation problems encountered in building the fill in the cramped quarters are not representative of field conditions, but the information gained may be helpful, and the writer has the following suggestions to offer. (1) It may be that the full length of a long fill should not be protected, but only a portion, after the fashion of the fuse plugs mentioned earlier. However, the flanks of adjacent non-overflow sections should be protected wherever high-velocity currents may attack. (2) The T-V gradings may seem complicated and hence expensive. However, natural deposits may be found to fit the specifications with little or no screening. In general, T-V gradings may be cheaper (in large quantites) than commercial gradings made for concrete. (3) With regard to the cost and durability of the wire sausages, the present investigation can offer little more than tentative information. The sausages used in the river flume test were made of wire removed from a high fence on the University Campus. Prices quoted by the Page Steel and Wire Division of the American Chain and Cable Company would result in the following approximate costs per square foot for a single layer of sausages made of 2" mesh chain link fabric:

W&M Gage-Material	Cost of mesh per square foot of surface protected	Ultimate Tensile stress Lbs per sq. in.	Relative Strength of wire
#6-Galvanized steel	$0.68	85,000	1.66
#9-Galvanized steel	0.43	90,000	1.00
#11-Stainless steel	1.25	130,000	.95
#12-Stainless steel	1.05	130,000	.70
#6-Aluminum	0.90	41,000	.81
#9-Aluminum	0.53	41,000	.45

All of those who report experience with steel wire protected by hot-dip zinc galvanizing for river protection work seem to agree that its life is 15 to 20 years. It seems likely that when used on highway fills and placed out of the water and not in direct contact with earth or sand, the life of galvanized wire would be more than 20 years. One cost-saving possibility would be to use stainless steel wire for those portions subject to frequent inundation, but if this is done special precautions must be taken to avoid electrolytic corrosion where contact is made with galvanized wire.

The Committee for the Regularization of the Rhine reported favorably on rock sausages, but stated that efforts to improve the useful life by using aluminum wire were unsuccessful as the wire was "not sufficiently resistant to withstand the stresses to which it is subjected during manufacture and the putting in place of the rollers."(9) Properly-designed mechanized equipment might make the use of aluminum wire possible. Most of the sausages used in the river flume test were end-filled, but the writer believes that the method used in the Allenspark test and for the first few sausages placed in the river flume was abandoned too soon, and that if suitable equipment were constructed it would be cheaper and permit a better job with less strain on the wire. The end-filling method has certain advantages, however, and could also be improved. For example, filled sausages could be transported by truck, which would permit their use for other purposes such as protecting piers abutments of bridges threatened by underscour.

From the theoretical standpoint, an important question remains unanswered, namely, what size sausages, filled with what size rock and woven of what size wire, will be required to resist current of a given depth and velocity? For the present purpose of protecting highway fills in Iowa this question apparently need not be answered until such time as the method has come into wide use and will bear further investigation to achieve maximum economy. If it is to be generally used for spillways, diversion channels, or bridge-pier or abutment protection, more information will have to be obtained.

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cooperation despite a tight testing schedule and the long delay due to insufficient river discharge.

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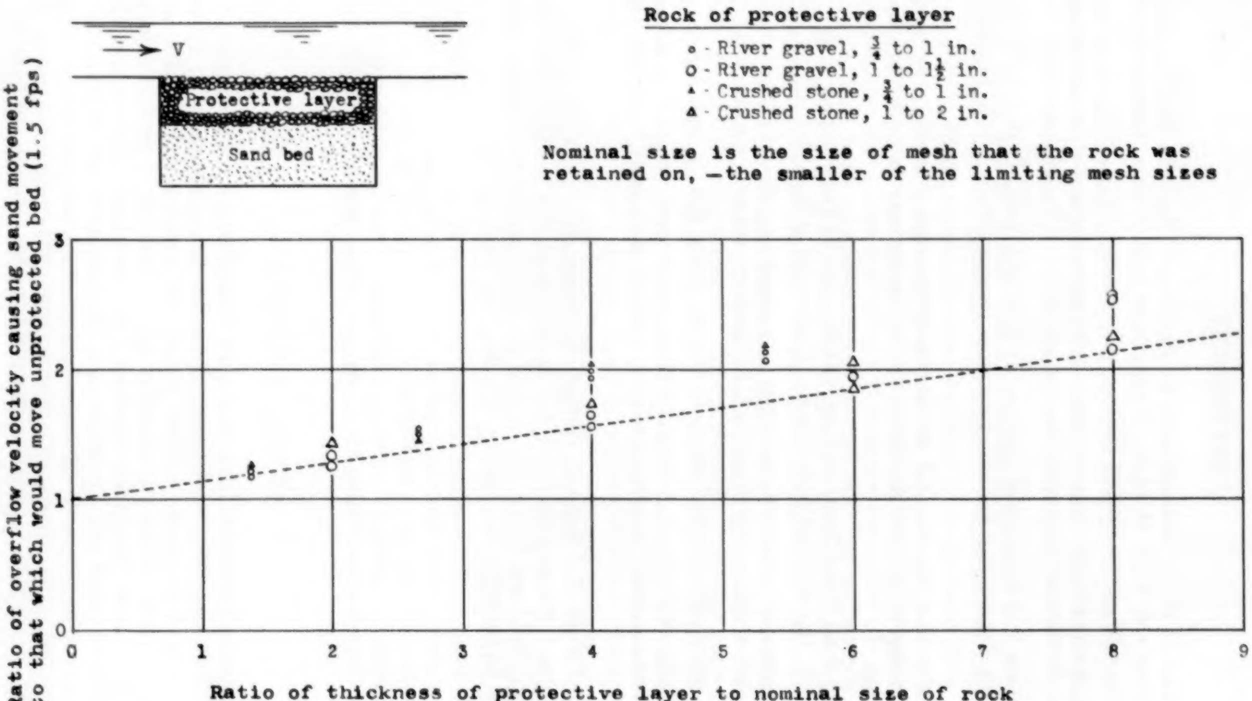

Fig. 1 - TESTS OF EFFECTIVENESS OF PROTECTIVE LAYER OF ROCK OF NEARLY UNIFORM SIZE

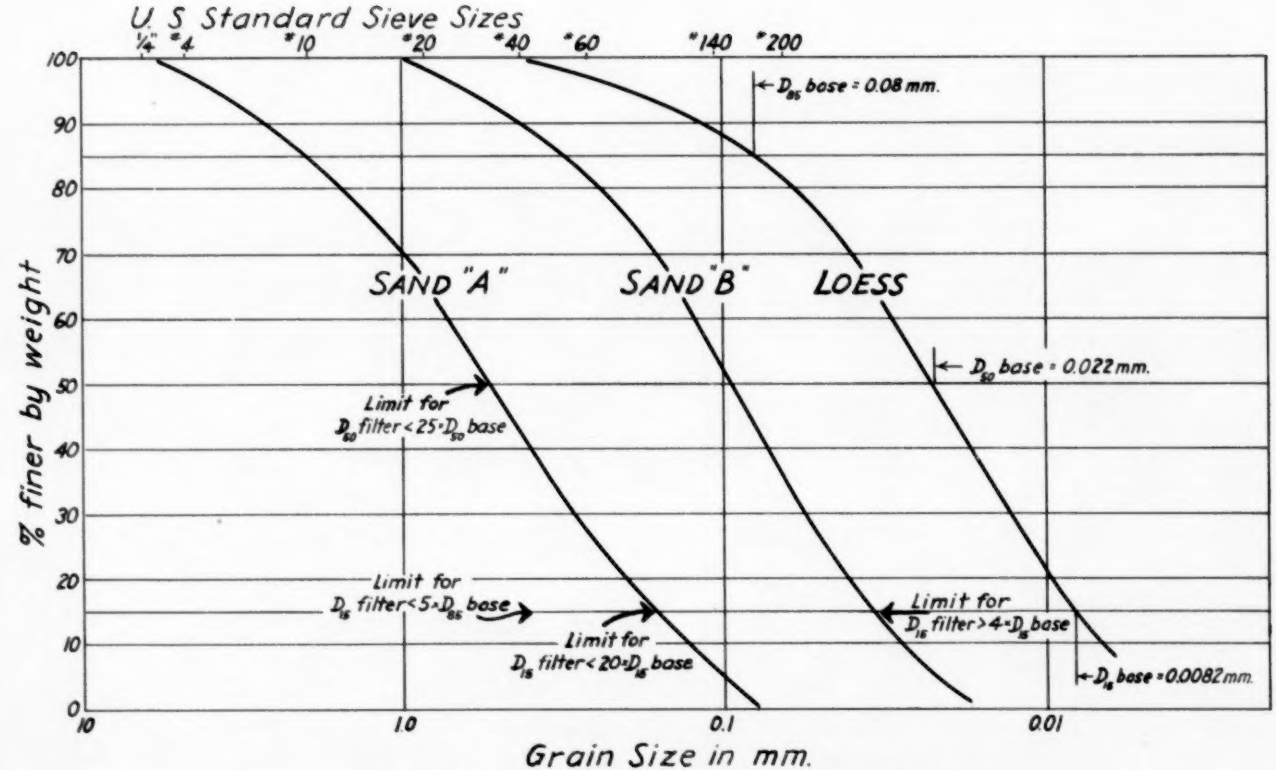

Fig. 2 - GRAIN-SIZE CURVES FOR T-V GRADINGS

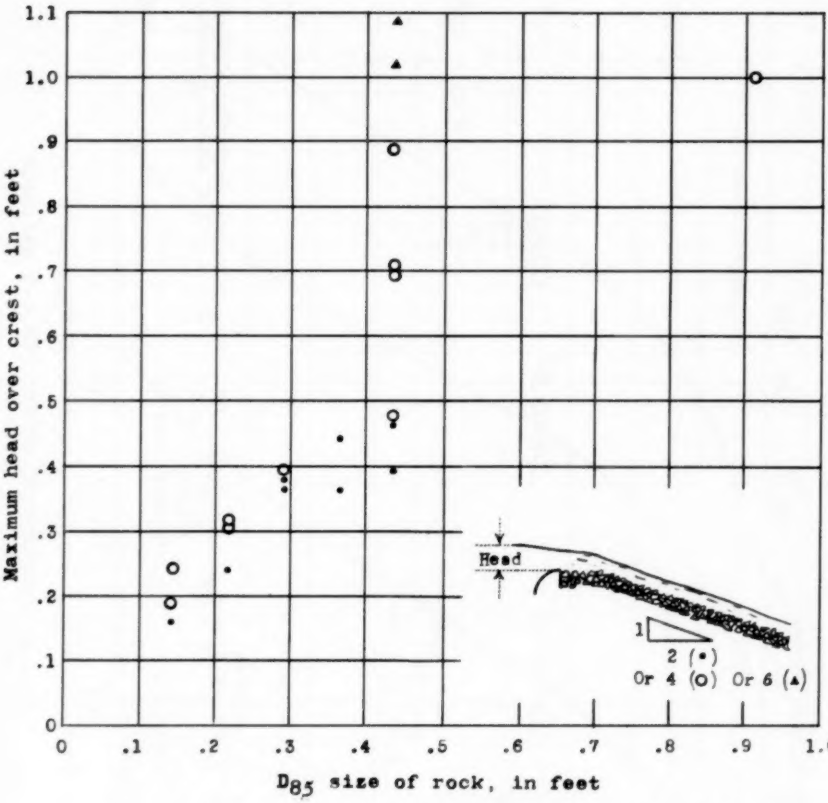

Fig. 3 - MAXIMUM HEADS FOR FLOW DOWN TYPICAL RIP-RAP SLOPES

At greater heads, the rock becomes unstable and is washed down the slope.